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EFFECT OF FUEL VOLATILITY AND MIXTURE TEMPERATURE ON THE

KNOCKING CHARACTERISTICS OF A LIQUID-COOLED SINGLE-CYLINDER

TEST ENGINE

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WASHINGTON

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

MEMORANDUM REPORT

for the

Army Air Forces, Air Technical Service Command

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SUMMARY

An investigation was conducted to determine the effect of fuel volatility on the relation between mixture temperature and knock-limited performance of a liquid-cooled single-cylinder test engine. Knock-limited mixture-response tests were run at inlet-air temperatures ranging from 150° to 380° F with AN-F-28 fuel and with technical grade of butane. For these two series of tests, the fuel was injected before a vaporization tank connected into the combustion-air system just before the engine. A similar series of tests was also run with 28-R fuel which was injected both before and after the vaporization tank.

The results of the tests show:

1. The mixture temperature at which the curve of indicated mean effective pressure plotted against mixture temperature becomes nonlinear is independent of the fuel volatility.

2. The knock-limited power output is slightly higher when the fuel has been reasonably well vaporized prior to induction into the engine than when the fuel is injected directly into the engine inlet pipe.

INTRODUCTION

At the request of the Army Air Forces, a series of tests is being conducted to determine the effect of engine-operating variables on the knock-limited power output of a liquid-cooled engine.

(See reference 1.) In the determination of the effect of decreasing
the inlet-mixture temperature on the knock-limited power output of
the engine, the following characteristic relations were observed:
(1) the increase in the knock-limited power was greater at lean
mixtures than at rich mixtures; (2) the fuel-air ratio at which the
maximum knock-limited power was observed decreased from a rich to a
a lean value; and (3) a value of the inlet-mixture temperature was
reached beyond which further decreases in this temperature caused
little or no further increase in the knock-limited power. These
effects are illustrated in figure 1, which is plotted from unpub-
lished data.

These three relations led to the hypothesis that incomplete
vaporization of the fuel at low inlet-mixture temperatures affected
the knock limits and that these relations were therefore dependent
upon the fuel volatility. The tests reported herein were conducted
at the NACA Cleveland laboratory during the latter part of 1944 in
order to determine whether fuel volatility was responsible for these
relations.

FUELS

Three fuels were used in the tests: AN-F-28, Amendment-2,
28-R, and a technical grade of n-butane (butane). The AN-F-28,
Amendment-2, and 28-R fuels had the following distillation char-
acteristics:

	10 per-cent point ($^\circ$F)	50 per-cent point ($^\circ$F)	90 per-cent point ($^\circ$F)
AN-F-28, Amendment-2	137	211	270
28-R	140	208	278

The A. S. T. M. distillation curves for these two fuels are pre-
sented in figures 2 and 3. The butane had a normal boiling point
of 31° F. The relation between the boiling temperature and pres-
sure for butane is shown in figure 4, which is plotted from data
obtained from reference 2.

APPARATUS

The tests were run in one cylinder of a liquid-cooled cylinder block mounted on a CUE crankcase, as described in reference 3. Knock was detected with a magnetic-vibration-type pickup coupled through an amplifier to an oscilloscope.

The induction system used with the engine is diagrammatically illustrated in figures 5 and 6. The combustion air, which was supplied by the central laboratory system, passed through a pressure-regulating valve and an electric heater before entering the surge tank. A thin-plate orifice was used to measure the air-flow rate.

From the surge tank the combustion air passed through the vaporization tank and the inlet elbow of the engine (fig. 5). The vaporization tank had a capacity of approximately 1 cubic foot. Several inclined baffles were mounted in the vaporization tank to provide additional surface for the evaporation of the fuel and to promote thorough mixing of the fuel with the air. Iron-constantan thermocouple junctions were mounted at the inlet (upstream from the injection nozzle) and at the outlet of the vaporization tank to determine the inlet-air and the mixture temperatures, respectively. The mixture thermocouple was mounted in such a position that any unvaporized fuel leaving the vaporization tank would tend to pass underneath the thermocouple and aid in preventing liquid fuel from reaching the junction.

For the tests with AN-F-28 and 28-R fuels, the fuel was metered to the engine by a variable-displacement fuel-injection pump driven by the engine and the flow rate was determined with a calibrated rotameter. Two fuel-injection nozzles were provided, one at the inlet to the vaporization tank and one just before the inlet elbow at the engine.

For the tests with butane, a special fuel system (fig. 6) was installed. Pressure was maintained in this system by immersing the fuel tank in a hot-water bath maintained at about 120° F. When the butane left the tank, it passed through a cooling coil, which reduced the fuel temperature sufficiently that it remained in the liquid state until it reached the fuel-injection nozzle.

TEST PROCEDURE

For the first and second series of tests, knock-limited mixture-response tests were run with AN-F-28 fuel and with butane. Five inlet-air temperatures, ranging from 145° to 385° F, were used in obtaining the data for both fuels. The third series of tests was

run with 28-R fuel at a constant fuel-air ratio of 0.10 and with
fuel-injection both before the vaporization tank and at the inlet
elbow of the engine; in this case, the inlet-air temperature was
the independent variable.

The following operating conditions were held constant for all
the tests:

Engine speed, rpm 3000
Compression ratio 6.65
Inlet-oil temperature, °F 185
Outlet-coolant temperature, °F 250
Coolant flow, gallons per minute   120
Spark advance, deg B.T.C.:
    Inlet 28
    Exhaust 34

RESULTS AND DISCUSSION

Comparison of AN-F-28 fuel and butane. - In general, the
knock-limited curves obtained in series 1 and 2 for the AN-F-28 fuel
and the butane (figs. 7 and 8) show the same general trends. At
the highest inlet-air temperature tested, the knock-limited indi-
cated mean effective pressure continued to increase as the fuel-air
ratio was enriched from the stoichiometric mixture to the richest
mixture at which data were taken. As the inlet-air temperature was
decreased, however, the performance curve developed a reverse bend
and peaked at a fuel-air ratio that became leaner as the temperature
was decreased. This characteristic was more pronounced for AN-F-28
fuel than for butane.

The cross plots of knock-limited indicated mean effective
pressure against mixture temperature for AN-F-28 fuel and butane
(fig. 9) show the same general trends. These curves are approx-
imately linear over the higher range of mixture temperatures but
bend and level off at lower mixture temperatures. The mixture tem-
perature at which these curves become nonlinear is the same for
both fuels at a comparable fuel-air ratio and therefore cannot be
considered to be a function of the fuel volatility.

The most pronounced difference in the cross plots for the two
fuels lies in the difference in slopes. This difference is
brought out more clearly by figure 10, in which is plotted the ratio
of the indicated mean effective pressure at a given mixture temper-
ature to the indicated mean effective pressure at a mixture temper-
ature of 275° F. This plot was made to eliminate differences in

the power levels of the two fuels and thus facilitate a comparison. At comparable fuel-air ratios, the butane shows a proportionately larger increase in indicated mean effective pressure than the AN-F-28 fuel for a given decrease in mixture temperature. As the fuel-air ratio is enriched, the difference in slopes is further accentuated.

In order to illustrate some effects on vaporization resulting from the differences in the volatilities of the two fuels, dew-point curves are presented in figure 11. These curves were obtained from equations published in references 4 and 5 and from data in reference 6; the methods of calculation are presented in the appendix. The curves for the AN-F-28 fuel (fig. 11(a)) show that at the lowest mixture temperature and at rich fuel-air ratios some liquid fuel is probably inducted into the engine. Because the dew-point temperatures of butane are very low (fig. 11(b)), it is extremely unlikely that any liquid can exist at the beginning of the compression stroke with this fuel.

Effect of fuel vaporization on knock-limited performance. - The results of tests conducted with 28-R fuel to determine the effect of fuel vaporization on the knock-limited power of the engine are shown in figure 12. For these tests, the degree of vaporization of the fuel was varied by changing the point of fuel injection (figs. 5 and 6).

The results show that the difference between the curves of knock-limited indicated mean effective pressure against inlet-air temperature is a maximum in the range of temperatures between 250° and 350° F. As the inlet-air temperature is decreased below this range, this difference becomes less, indicating that the inlet-air temperature is too low to vaporize the fuel with injection before the vaporization tank. At inlet-air temperatures above this range, the decrease in the difference between the two curves indicates that the temperature of the inlet air is sufficiently high to vaporize the fuel more completely with fuel injection at the inlet elbow.

SUMMARY OF RESULTS

The results of tests run on a single cylinder from a liquid-cooled engine block with fuels of different volatilities, butane and AN-F-28, and with different degrees of fuel vaporization using 28-R show that:

1. The mixture temperature at which the curve of indicated mean effective pressure plotted against mixture temperature becomes nonlinear is independent of the fuel volatility.

2. The knock-limited power output of the engine is slightly higher when the fuel has been reasonably well vaporized prior to induction into the engine than when the fuel is injected directly into the engine inlet pipe.

Aircraft Engine Research Laboratory,
        National Advisory Committee for Aeronautics,
                Cleveland, Ohio, April 24, 1945.

APPENDIX

DEW-POINT CALCULATIONS

Calculation of dew-point curves for AN-F-28, Amendment-2, fuel. -
No experimental data have been published on the dew points of cur-
rent aircraft fuels at different fuel-air ratios and total pressures.
Reference 4 outlines a method whereby such dew points may be calcu-
lated for total pressures up to one atmosphere. For the purpose of
this report, the equations of reference 4 were assumed to hold true
for total pressures up to 80 inches of mercury absolute and for the
range of fuel-air ratios from 0.05 to 0.125.

When equations (31), (35), (38), and (42) in reference 4 are
combined, the following equation is obtained:

$$t_{dp} = \left\{ 0.132 + 0.109 \log_{10} \left[F/A \ (0.0348 \ P - 0.04) \right] \right\} (t_{90\%} + 460)$$

$$+ \frac{2}{3} t_{90\%} - 8.95 \sqrt{S} - 106.5 \tag{1}$$

where

t_{dp} dew-point temperature at a given fuel-air ratio and at a
given total pressure, °F

F/A fuel-air ratio

P total pressure, in. Hg absolute

$t_{90\%}$ temperature of 90 percent point on A.S.T.M. distillation
curve, °F

S slope of A.S.T.M. distillation curve at 90 percent point,
°F per percent distilled

From the distillation curve presented in figure 2, values of
$t_{90\%}$ and S were determined to be as follows:

$$t_{90\%} = 270^{\circ} \ F$$

$$S = 3.9^{\circ} \ F \ \text{per percent distilled}$$

Substitution of these values in equation (1) yields the result:

$$t_{dp} = 79.6 \log_{10}\left[F/A\ (0.0348\ P - 0.04)\right] + 152.4 \qquad (2)$$

Equation (2) was then used to calculate the curves of figure 11(a).

Calculation of dew-point curves for butane. - Because the butane was a nearly pure hydrocarbon, it was considered more feasible to calculate the partial pressure of the fuel in the fuel-air mixture and then determine the saturation temperature from the vapor-pressure curve than to use the method of reference 4.

The partial pressures of the butane were determined by means of Dalton's law:

$$\frac{P_1}{M_1} = \frac{P_2}{M_2} \qquad (3)$$

where

P   pressure

M   molecular weight, moles

For use in the tests reported herein, the equation was written in the form:

$$P_f = \frac{M_f P_m}{M_m} \qquad (4)$$

where

P   pressure, in. Hg absolute

M   molecular weight, lb-moles

f   fuel

m   mixture

When the molecular weight of 58 for butane and 28.95 for air are substituted, the equation becomes:

$$P_f = \frac{0.01724 \ P_m \ (F/A)}{0.0339 + 0.01724 \ (F/A)} \qquad \qquad (5)$$

From this equation the partial pressures of the fuel were calculated.

In order to determine the saturation temperatures corresponding to the partial pressures, the boiling-point curve (fig. 4) was extrapolated by means of a Dühring line plot. A description of type of construction will be found in reference 5. The equation of the Dühring line was determined to be:

$$t_w = 1.084 \ t_f + 178.7 \qquad \qquad (6)$$

where

t_w saturation temperature of reference liquid (water) at a given pressure, $°F$

t_f saturation temperature of fuel at same pressure, $°F$

Data on the thermodynamic properties of water used in connection with the Dühring line plot were obtained from reference 6.

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2. Anon.: Handbook of Chemistry and Physics. Chemical Rubber Publishing Co. (Cleveland), 24th ed., 1940, pp. 1836-1837.

3. Waldron, C. D., and Biermann, A. E.: Method of Mounting Cylinder Blocks of In-Line Engines on CUE Crankcases. NACA RB No. E4G27, 1944.

4. Bridgeman, Oscar C.: Equilibrium Volatility of Motor Fuels from the Standpoint of Their Use in Internal Combustion Engines. Res. Paper 694, Nat. Bur. Standards Jour. Res., vol. 13, no. 1, July 1934, pp. 53-109.

5. Hougen, O. A., and Watson, K. M.: Industrial Chemical Calculations.
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6. Keenan, Joseph H., and Keyes, Frederick G.: Thermodynamic Proper-
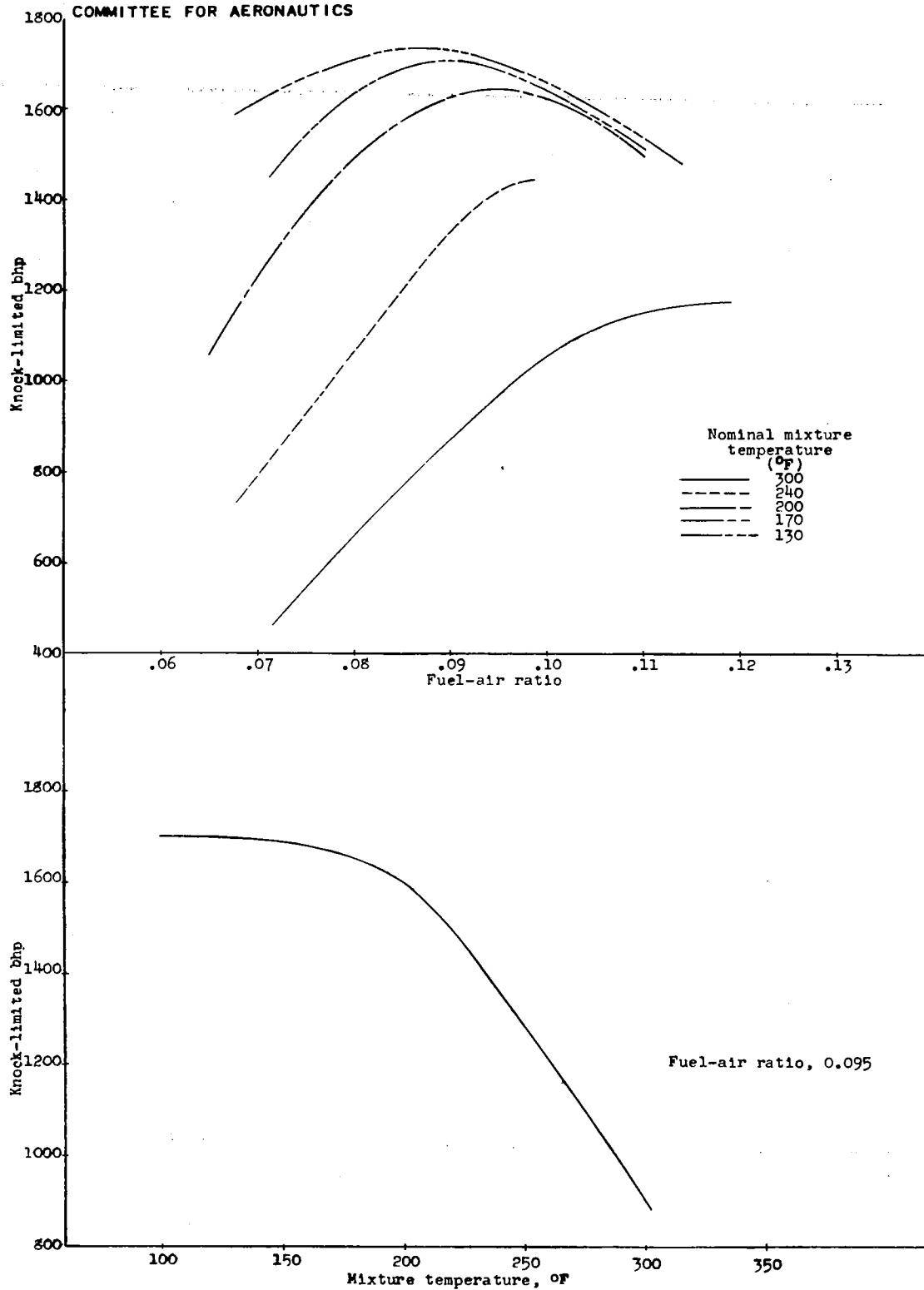   ties of Steam. John Wiley & Sons, Inc., 1936.

Nominal mixture
temperature
($^\circ$F)
——— 300
----- 240
— — 200
—·—· 170
—··—·· 130

Knock-limited bhp

Fuel-air ratio

Knock-limited bhp

Fuel-air ratio, 0.095

Mixture temperature, $^\circ$F

Figure I. — Effect of mixture temperature on knock—limited performance
of liquid—cooled multicylinder engine at 3000 rpm. (Plotted from un—
 published data.)

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Fuel, AN-F-28

137-1
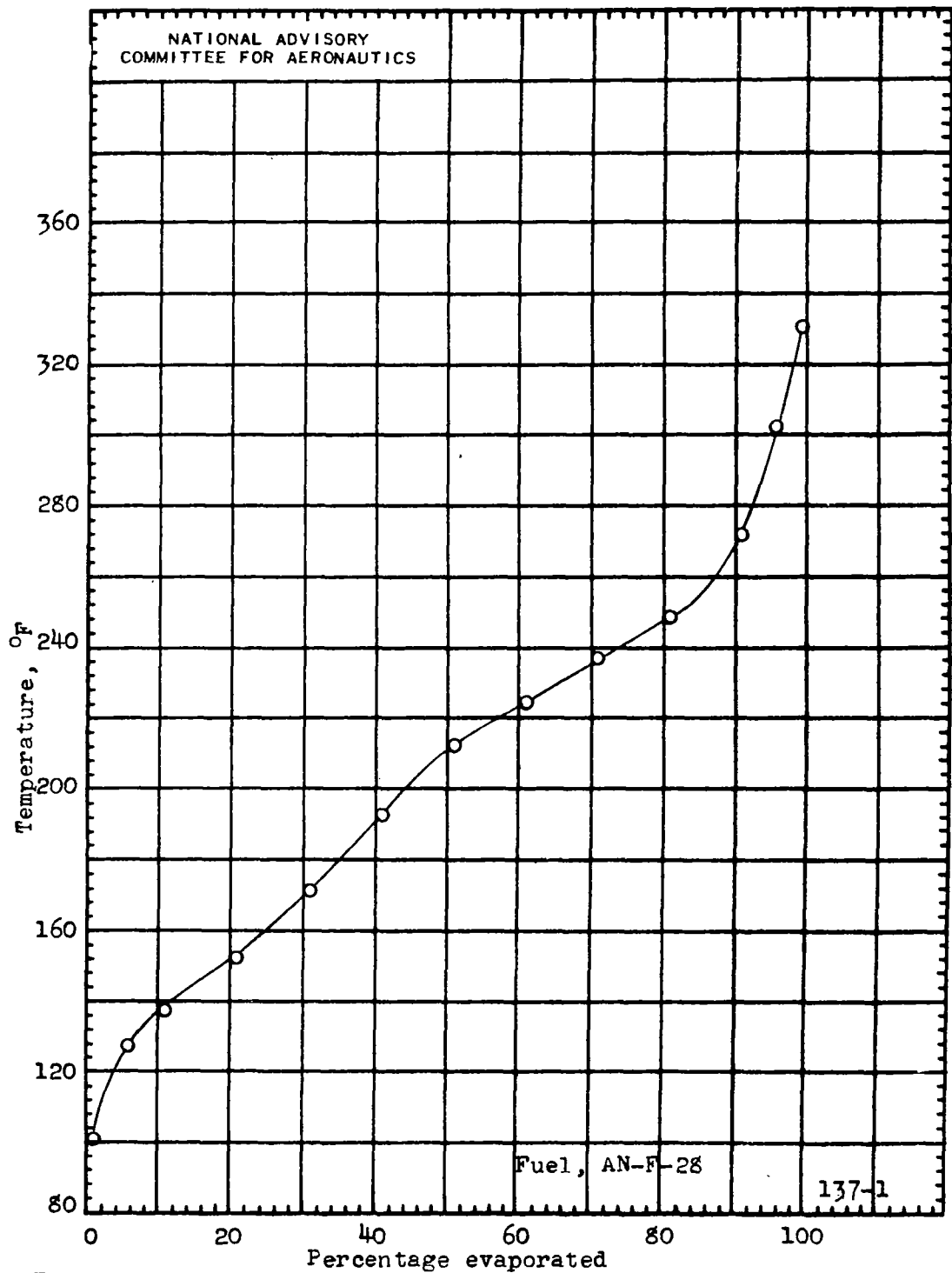
Figure 2. - A.S.T.M. distillation curve for AN-F-28, Amendment-2,
fuel used in the first series of tests. Recovery, 98.0 percent;
residue, 0.8 percent.
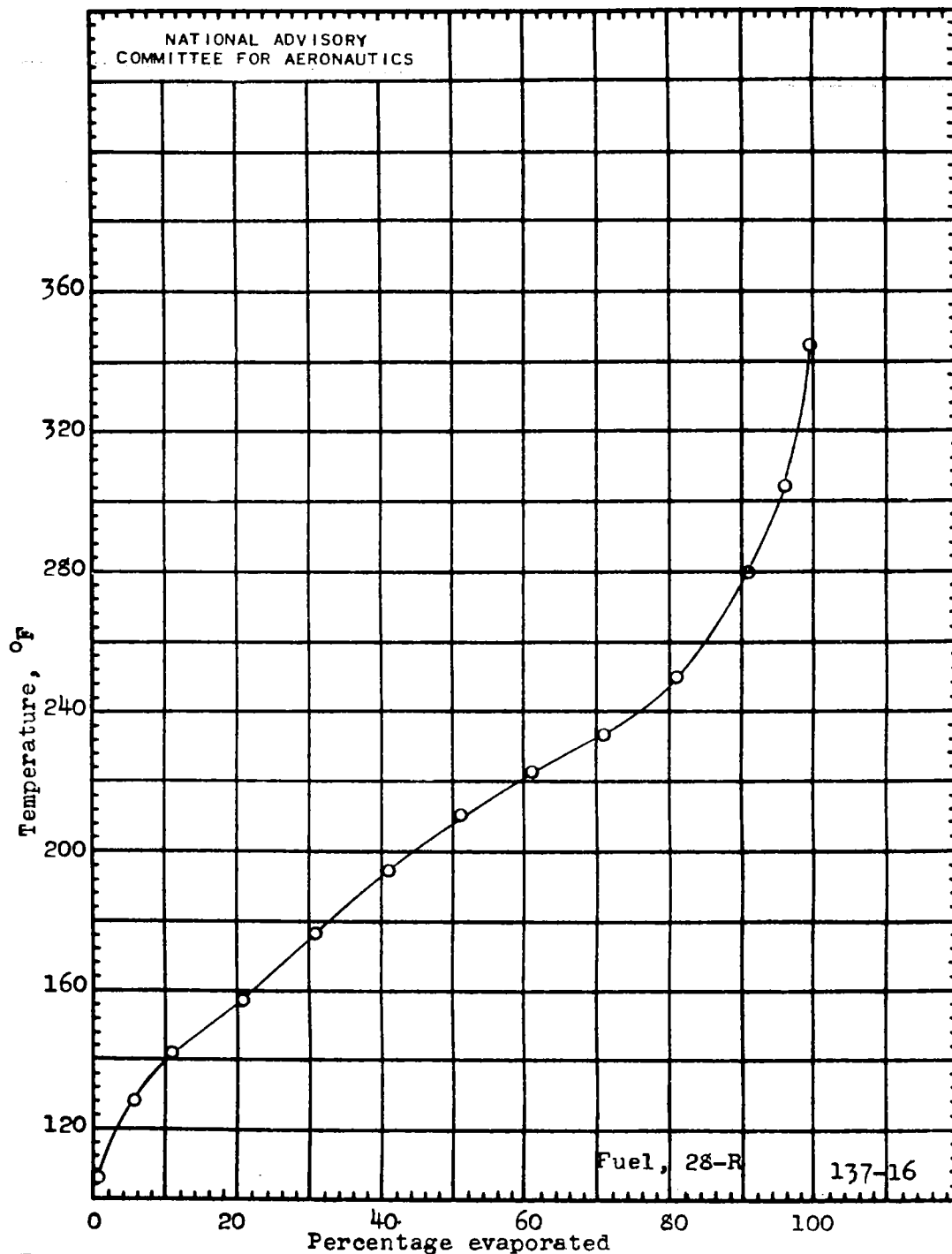
Figure 3. - A.S.T.M. distillation curve for 28-R fuel used in the third series of tests. Recovery, 98.2 percent; residue, 0.6 percent.
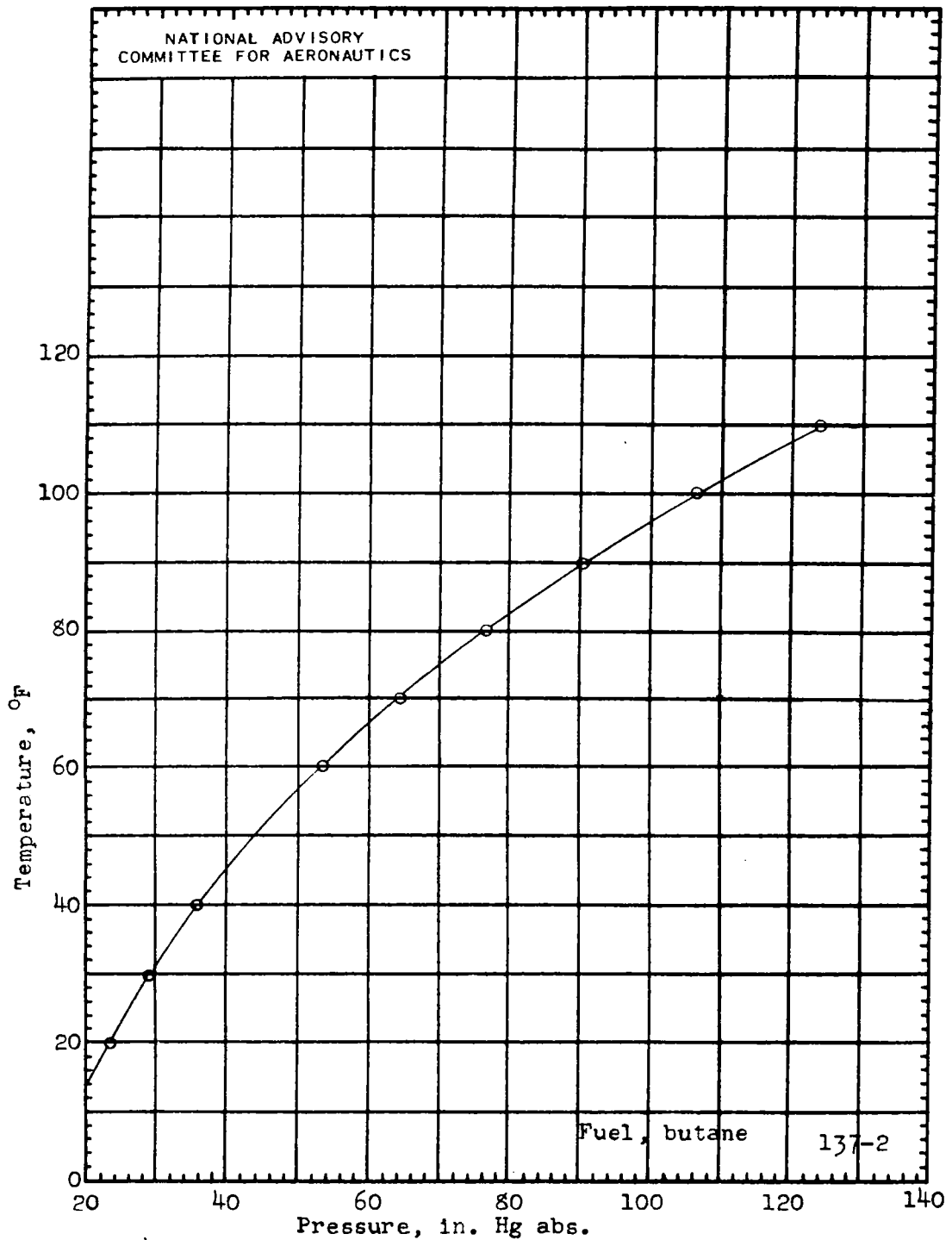
Figure 4. – Variation of boiling temperature of butane with pressure. (Data from reference 2.)

Inlet-air thermocouple

Fuel-injection nozzle

Vaporization tank

Inlet-air pressure tap

Engine cylinder

Surge tank

Mixture thermocouple
(used with injection at
top of vaporization tank only)

Fuel-injection nozzle
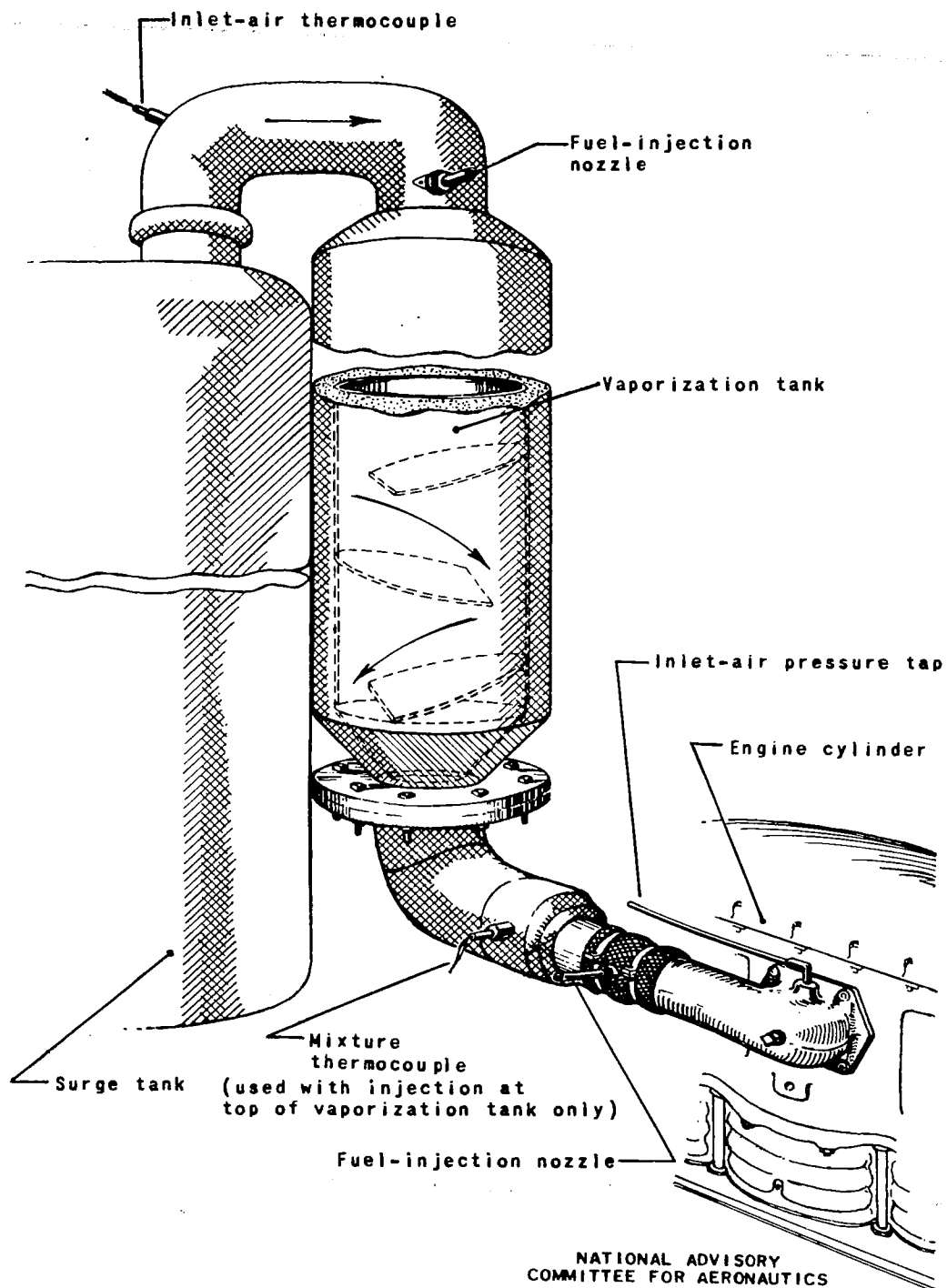
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Figure 5. — Diagram of induction system used with single-cylinder
liquid-cooled test engine.
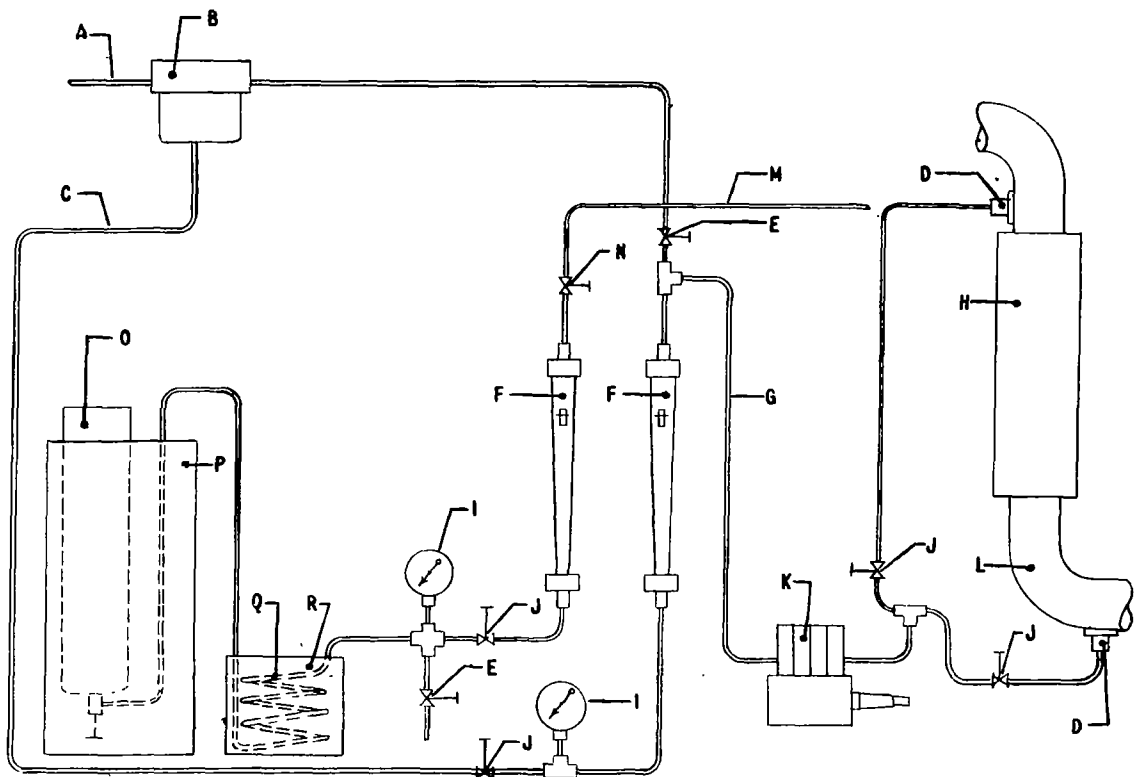
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Low-volatility fuel system

A Fuel line from barrel pump
B Constant head tank
C Fuel line to flowmeter
D Fuel-injection nozzle
E Venting valve
F Fuel flowmeter
G Fuel line to engine
H Vaporization tank
I Pressure gage
J Shut-off valve
K Variable displacement
   fuel-injection pump
L Engine-inlet pipe

Butane system

M Fuel line to
   injection nozzle
N Throttling valve
O Butane tank
P Hot-water bath
Q Cooling coil
R Ice container

Figure 6. — Diagram of fuel systems used with single-cylinder liquid-
cooled test engine.
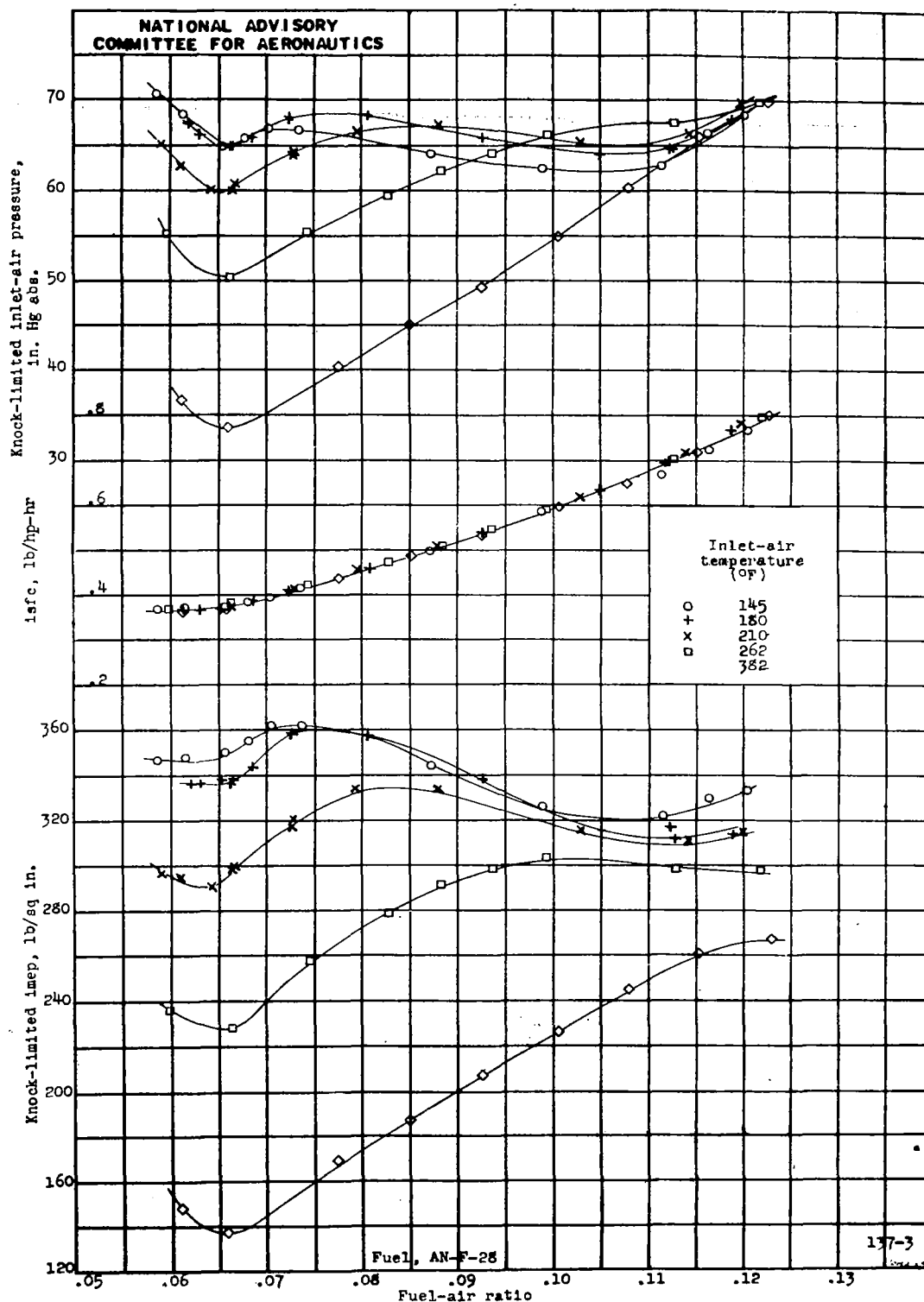
Figure 7. – Effect of inlet-air temperature on knock-limited performance
of single cylinder from liquid-cooled engine with AN-F-28, Amendment-2,
fuel. Engine speed, 3000 rpm; compression ratio, 6.65; inlet-oil tem-
perature, 185° F; outlet-coolant temperature, 250° F; spark advance:
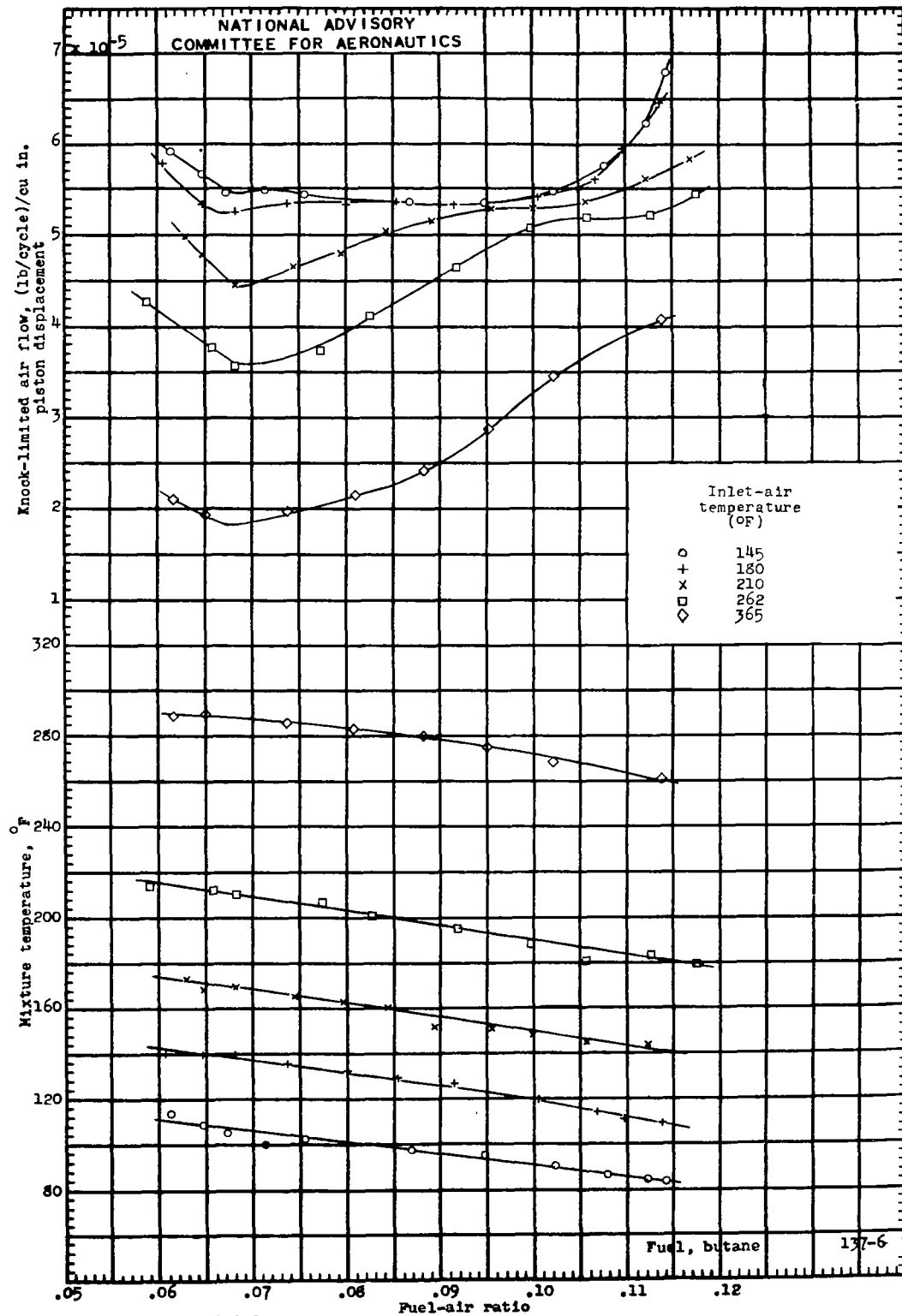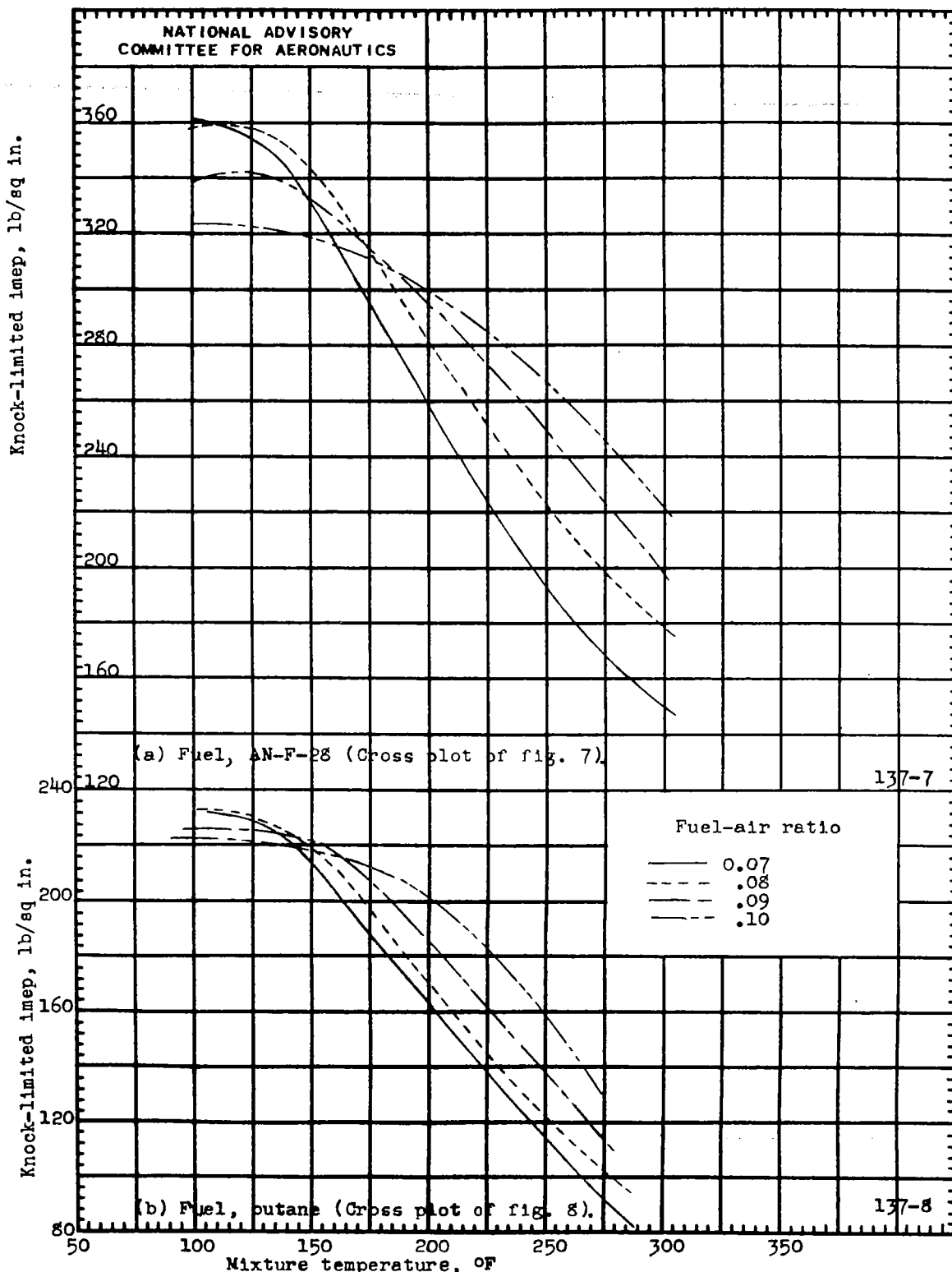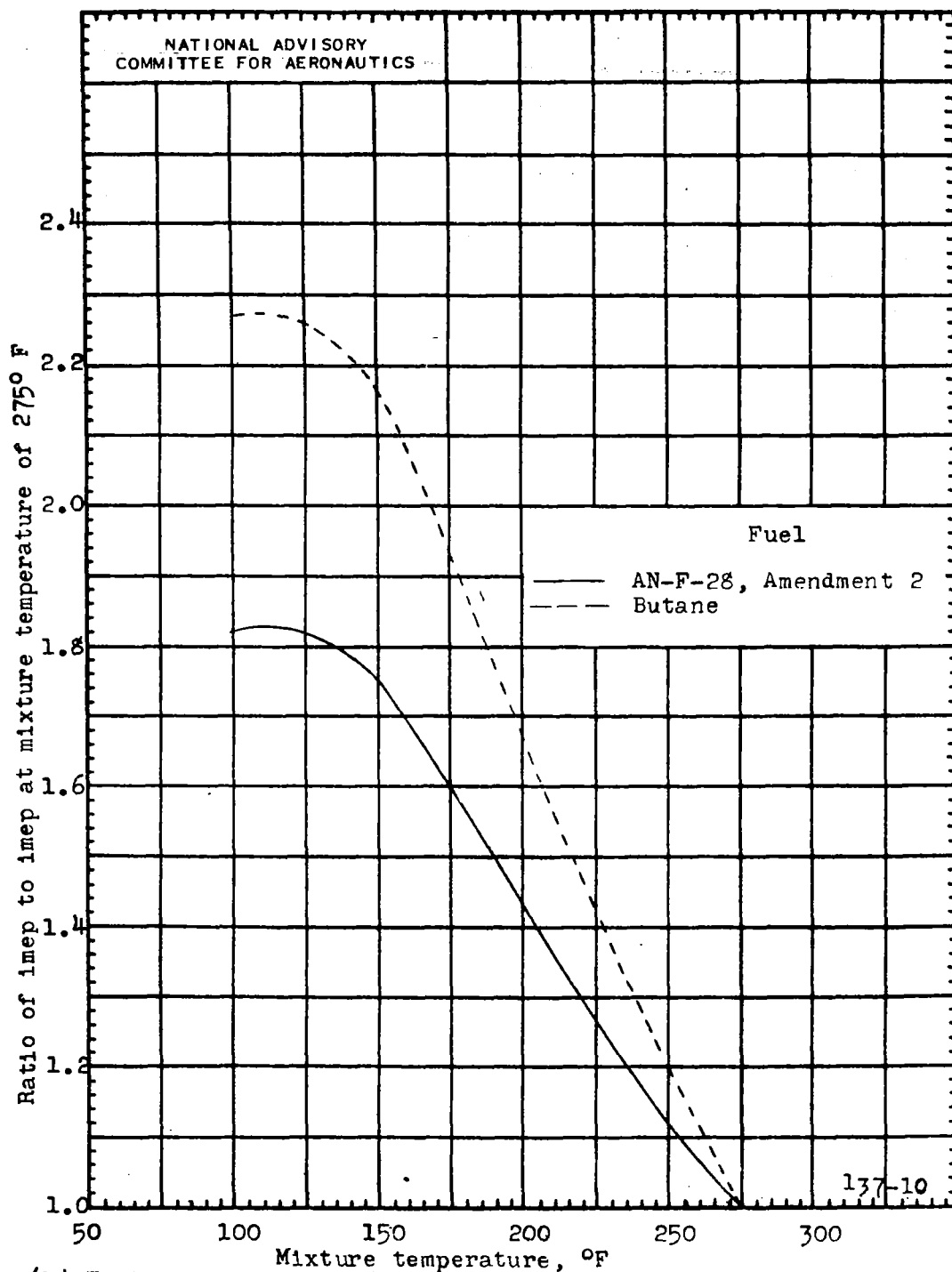inlet, 28° B.T.C.; exhaust, 34° B.T.C.
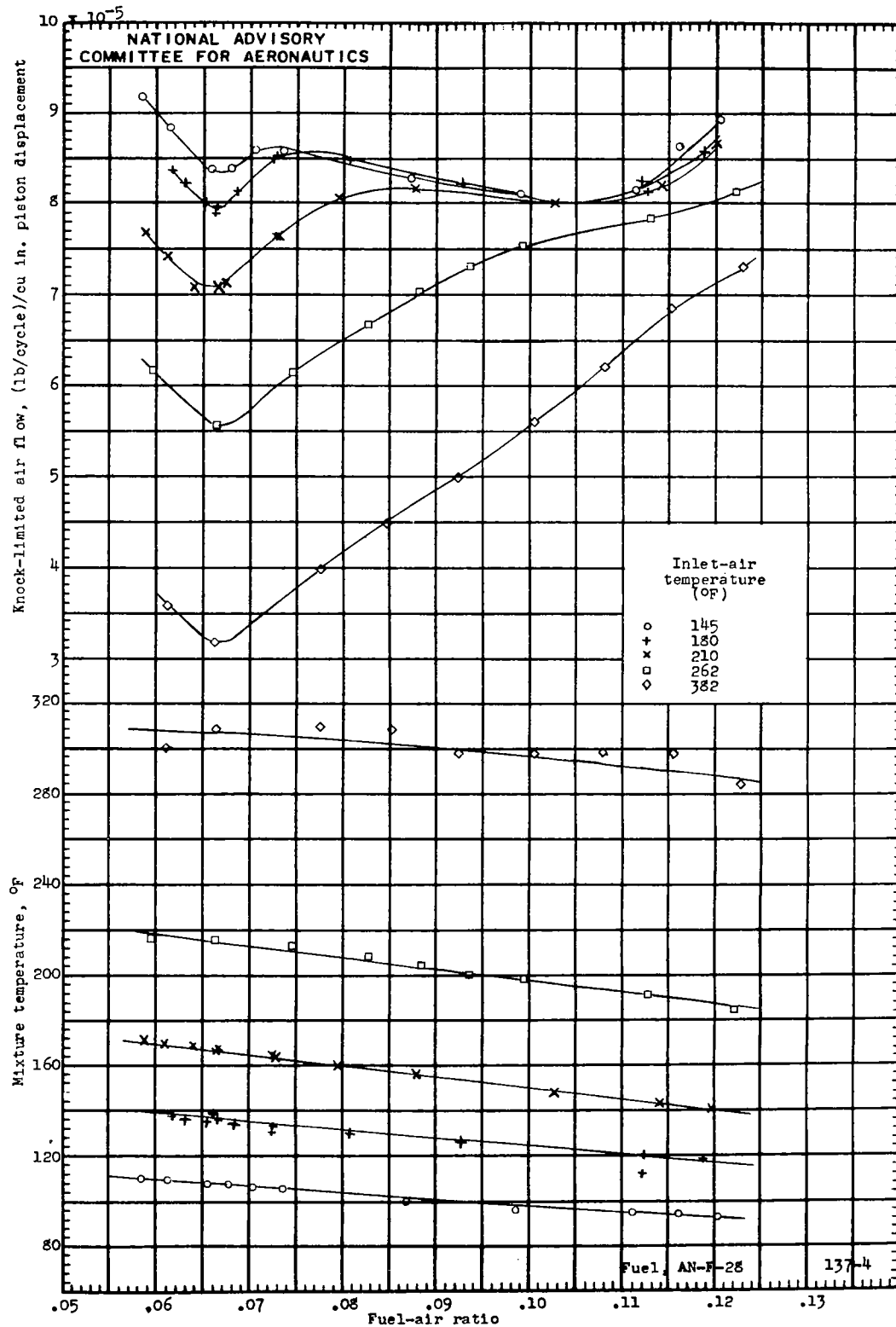
Figure 7. - Concluded.
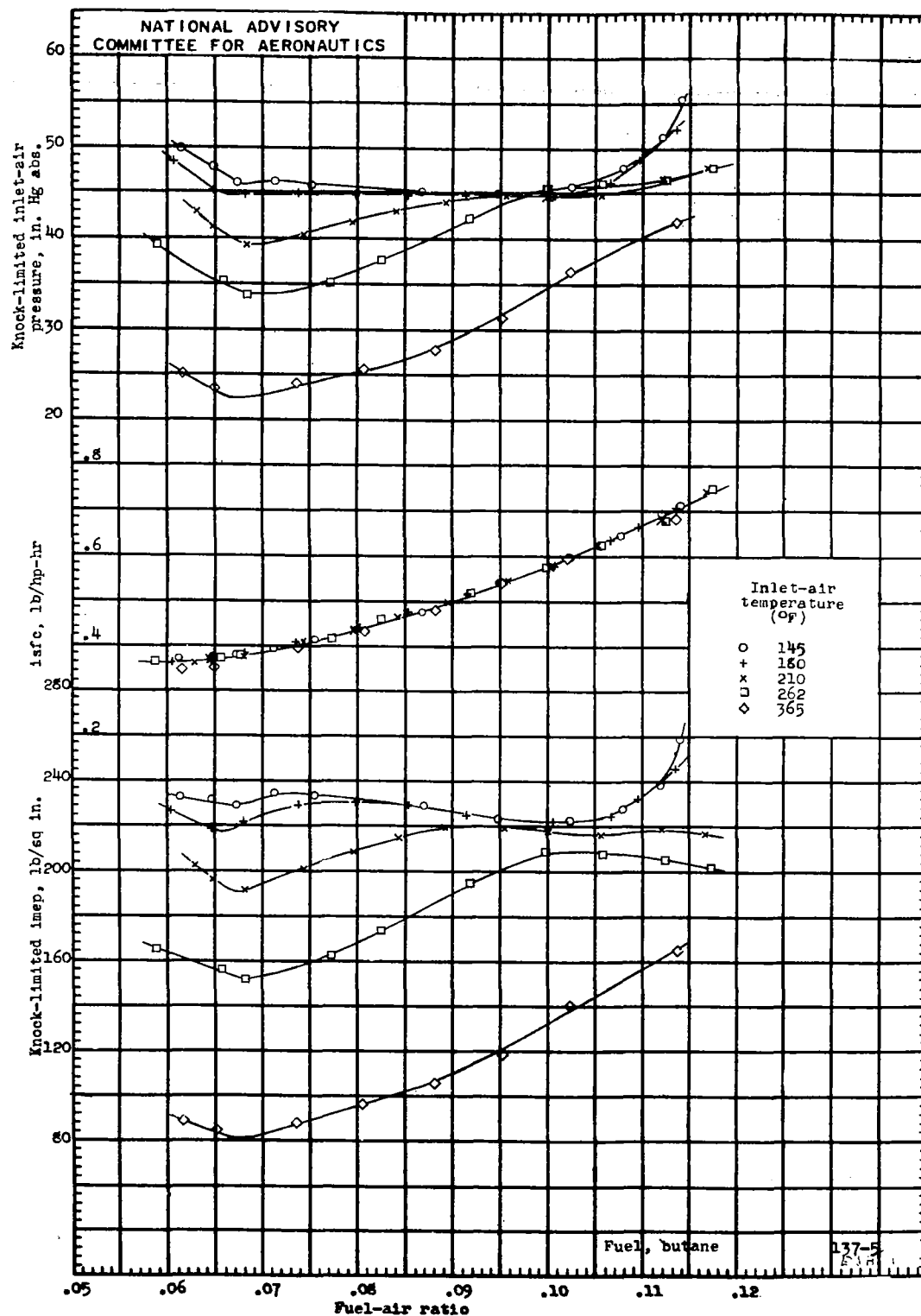
Figure 8. — Effect of inlet-air temperature on knock-limited performance
of single cylinder from   liquid-cooled engine using butane as a fuel.
Engine speed, 3000 rpm; compression ratio, 6.65; inlet-oil temperature,
185° F; outlet-coolant temperature, 250° F; spark advance: inlet, 28°
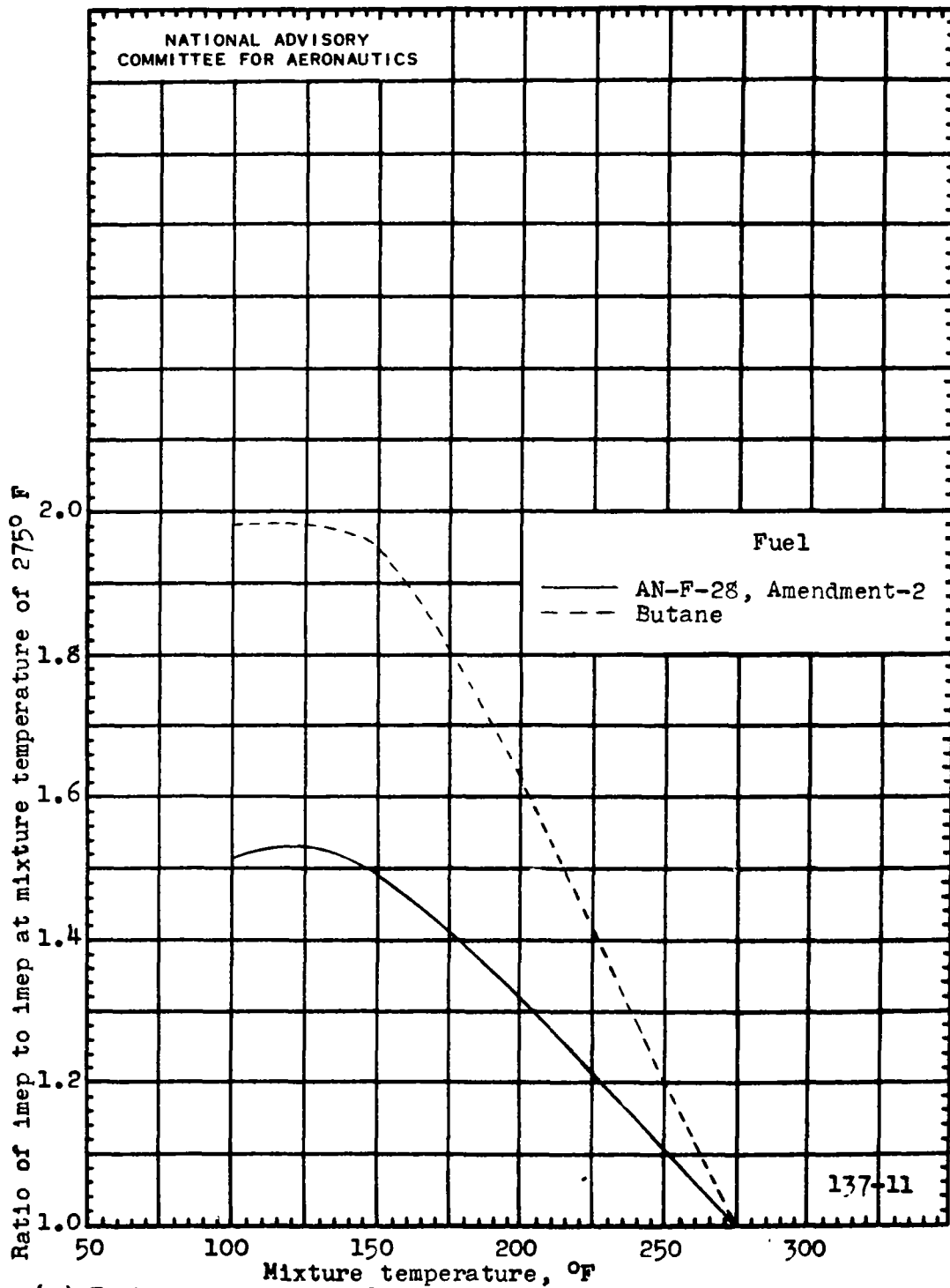B.T.C.; exhaust, 34° B.T.C.

Figure 8. — Concluded.

Figure 9. – Variation of knock-limited indicated mean effective pressure with mixture temperature for AN-F-28, Amendment-2, fuel and butane.
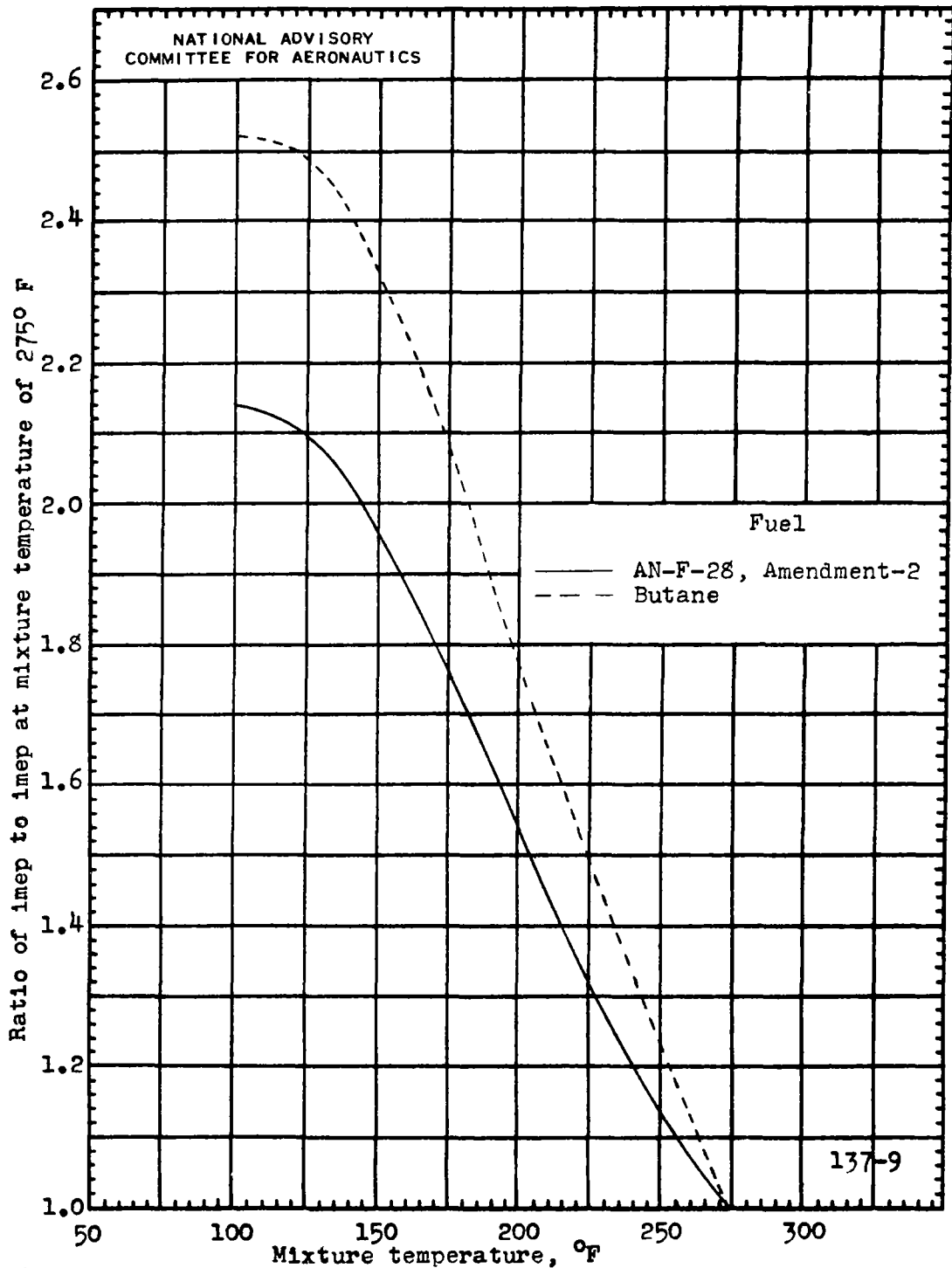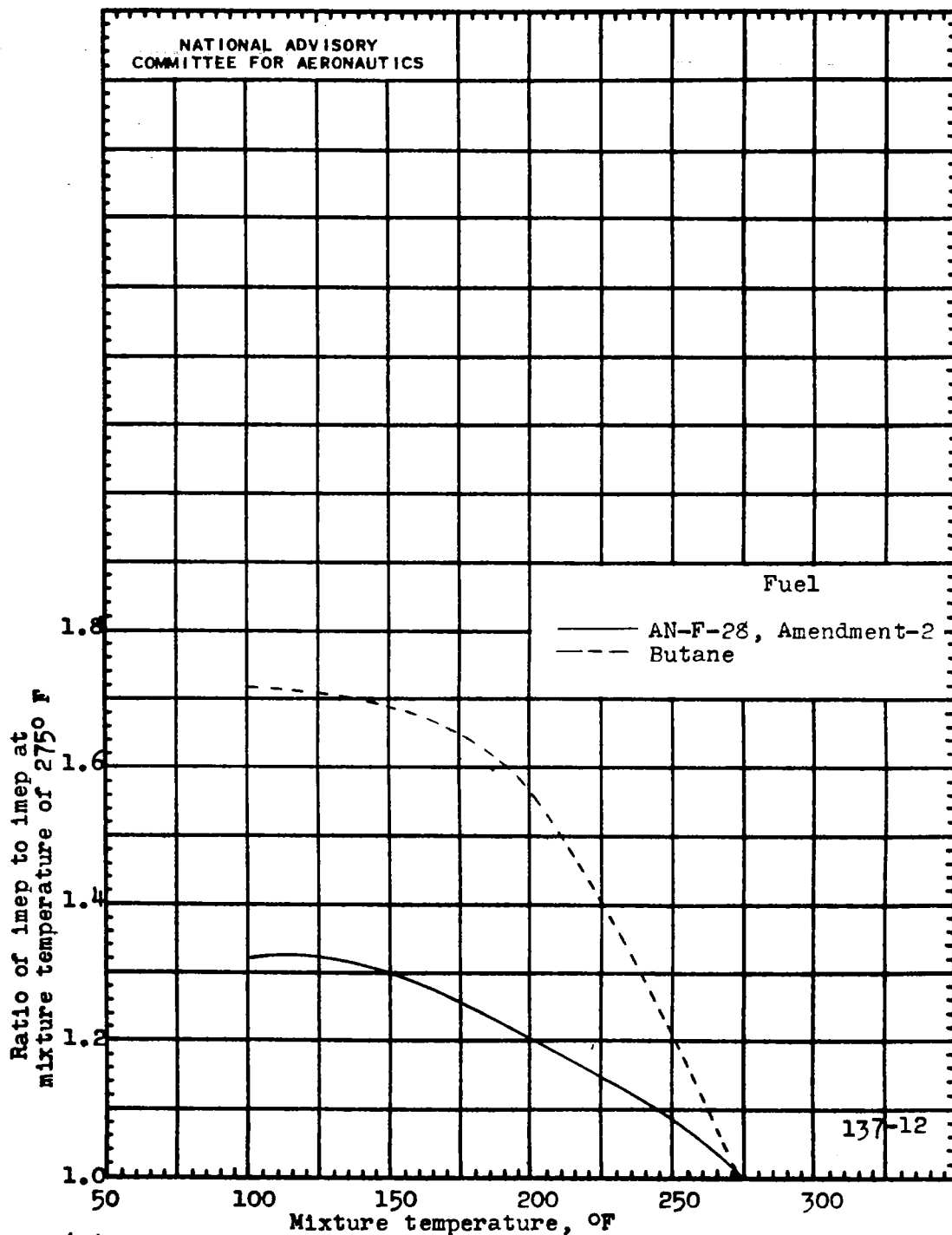
(a) Fuel-air ratio, 0.07.

Figure 10. - Variation of relative knock-limited power output with mixture temperature for AN-F-28, Amendment 2, and butane. (Data from figs. 7 and 8.)
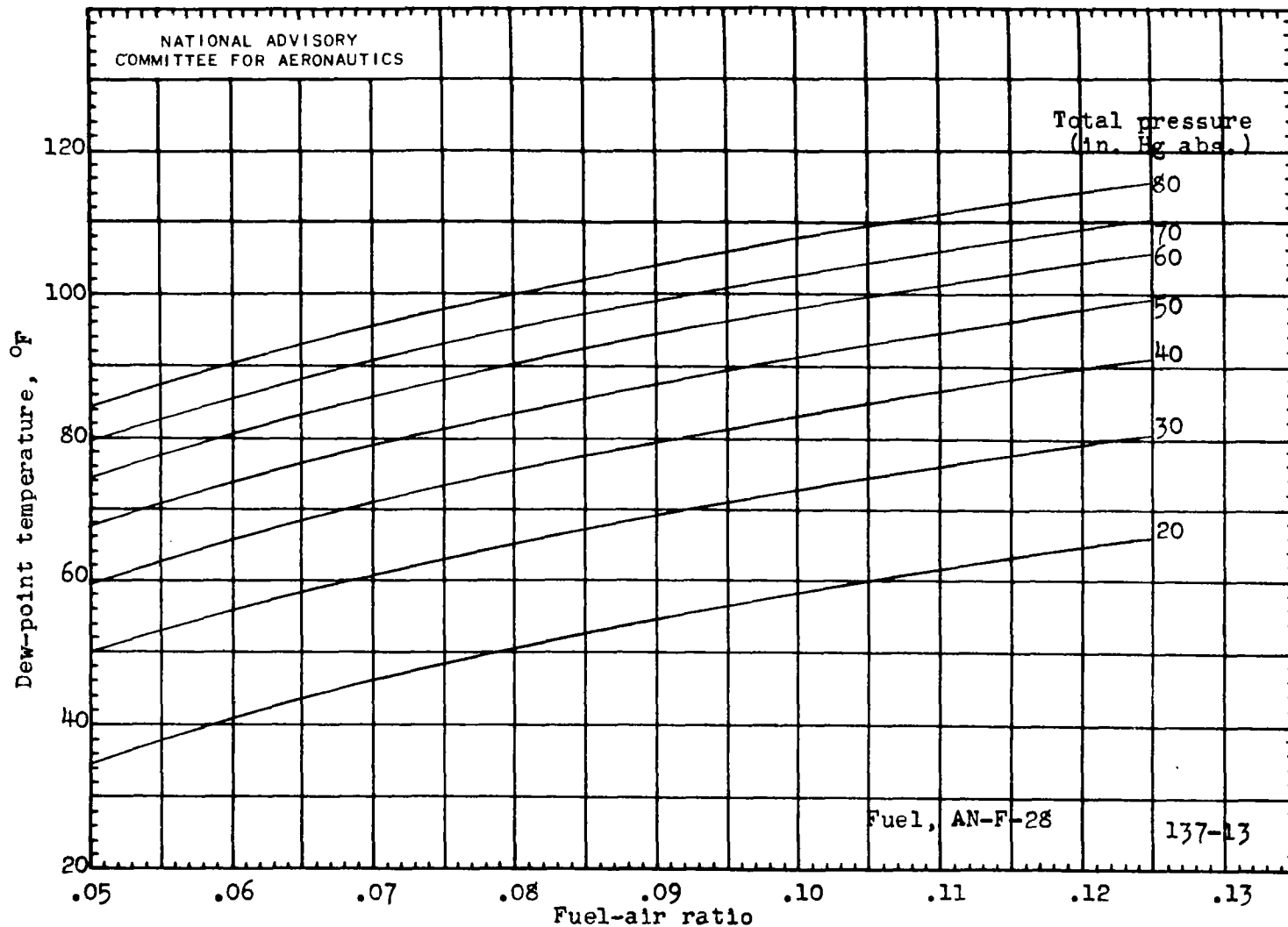
(b) Fuel-air ratio, 0.08.
Figure 10. - Continued.

(c) Fuel-air ratio, 0.09.
Figure 10. - Continued.

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Fuel

——— AN-F-28, Amendment-2
— — — Butane

137-12

Ratio of lmep to lmep at mixture temperature of 275° F
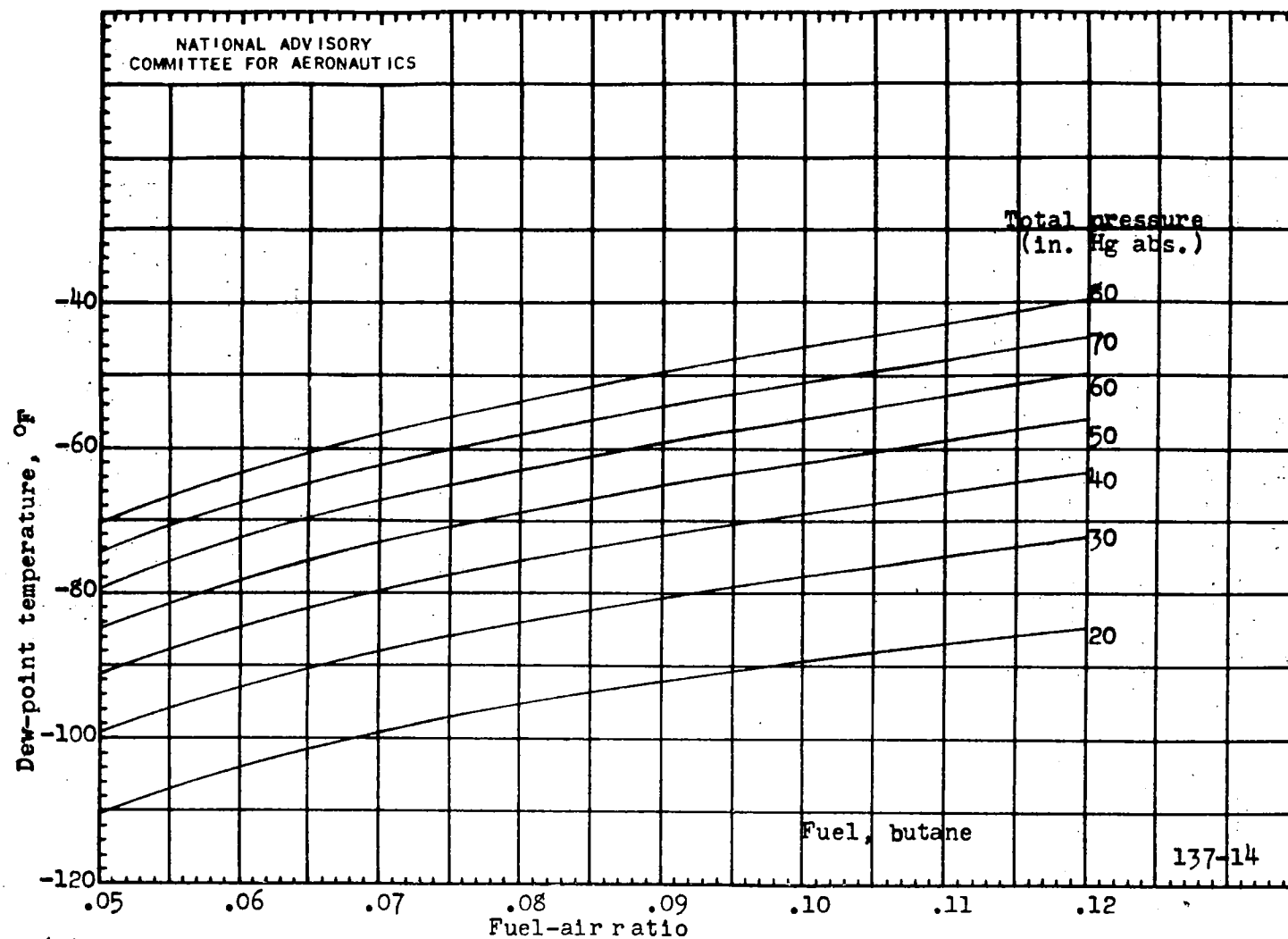
Mixture temperature, °F

(d) Fuel-air ratio, 0.10.
Figure 10. - Concluded.

(a) Fuel, AN-F-28.
Figure 11. - Dew-point temperatures for AN-F-28, Amendment-2, and butane at various total pressures.

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Total pressure
(in. Hg abs.)

80
70
60
50
40
30
20

Fuel, butane

137-14

Dew-point temperature, °F

Fuel-air ratio

(b) Fuel, butane.
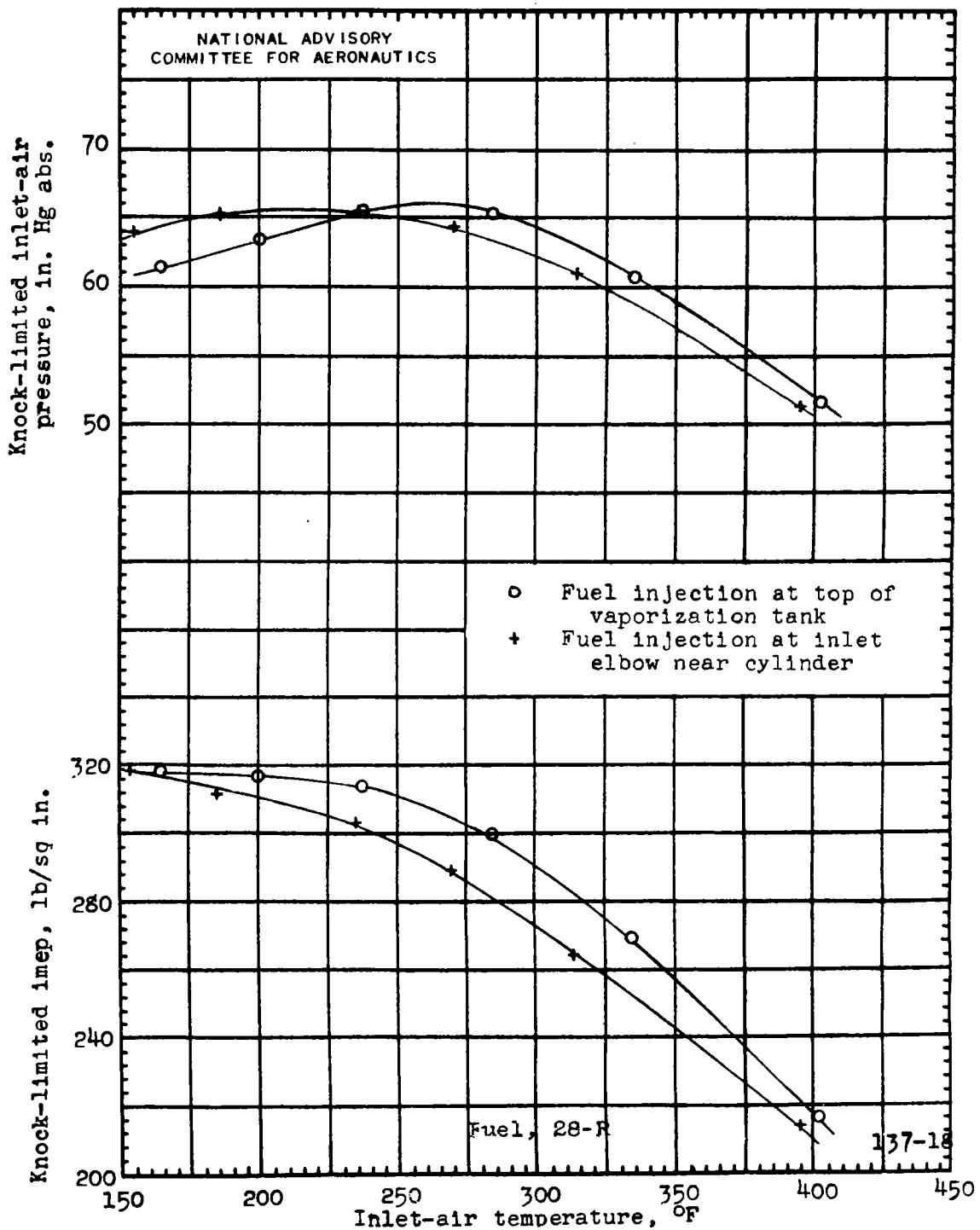Figure 11. - Concluded.

Figure 12. – Effect of fuel vaporization on knock–limited performance of single cylinder from liquid–cooled engine. Engine speed, 3000 rpm; fuel–air ratio, 0.10; compression ratio, 6.65; inlet–oil temperature, 185° F; outlet–coolant temperature, 250° F; spark advance: inlet, 28° B.T.C.; exhaust, 34° B.T.C.